Exploring the Origin and Impact of Pattern Dependent Focus Shifts and Asymmetry on Bossung Curves through Rigorous EUV Mask Simulations

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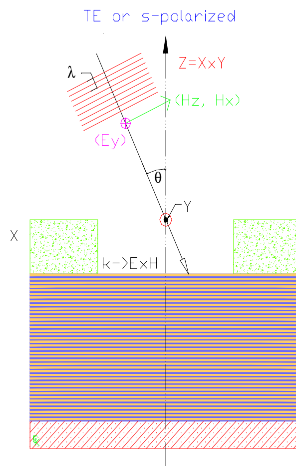
Motivation of Work

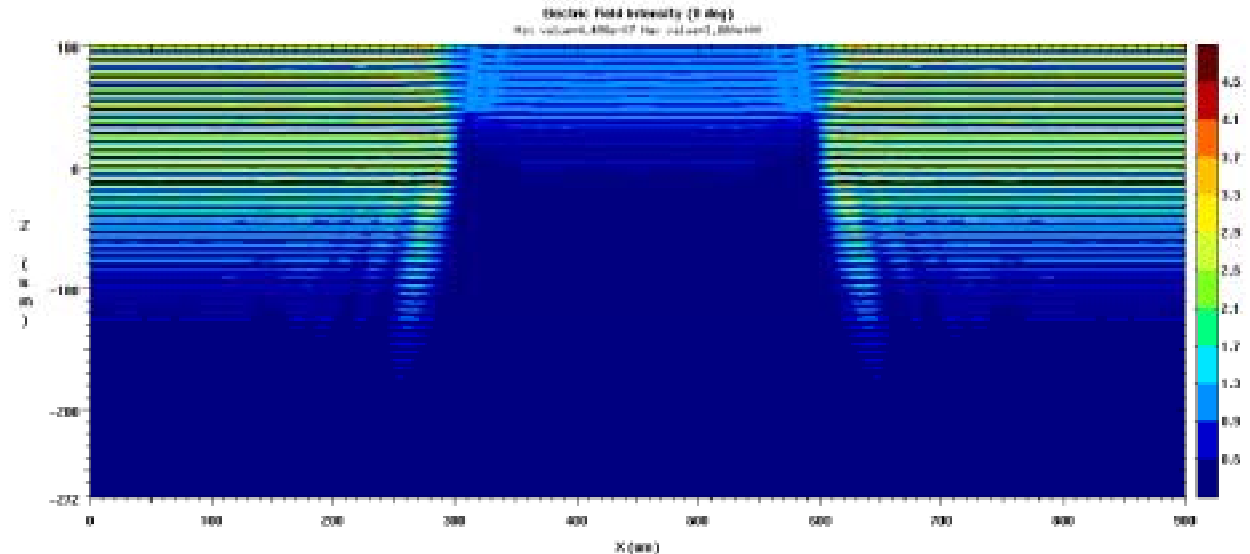
- EUV Masks generally require modeling by rigorous Maxwell Solvers.
  - Mask Thickness > 30 times the wavelength (@13.4 nm)
  - Non-normal incidence causes asymmetry in scattering of diffraction orders. Incidence angles can vary between 0 to ~6 degrees for higher NA systems.
  - The Electric Field Amplitude on top of the absorber is never zero as for the binary chrome mask case.
  - The Phase of the electric field can vary significantly over bright/dark regions.
  - Incidence Angles can vary between 0 and 5-6 degrees for higher NA systems.

Given the differences in the EUV mask structure (from the thin mask) what artifacts does a thick mask generate and how significantly do they deviate from the ideal case?

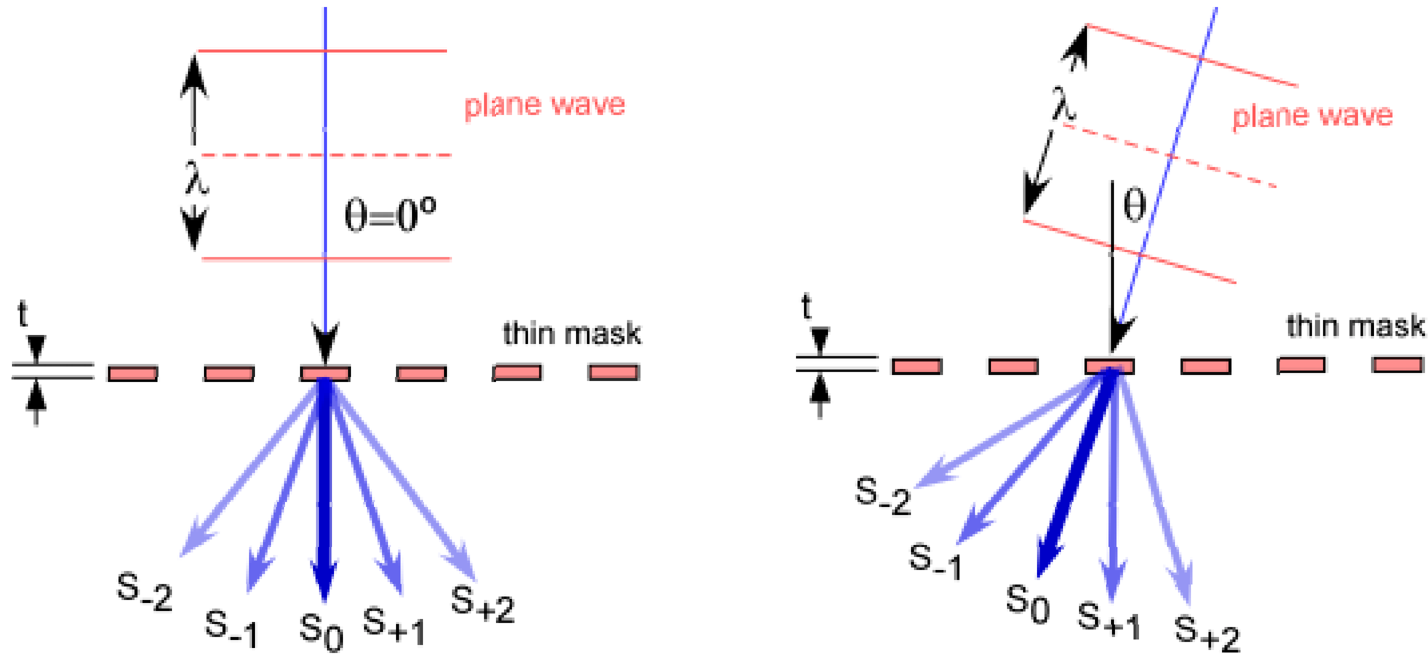
Rigorous Simulation of Mask:

- TE Polarization of vertical lines at θ= 0º, 3º, 5º, 6º
- Constant scattering approximation for illumination condition.
- Multilayers: 40 Si/Mo bilayers
- Absorber: 100 nm of Ta, 50 nm SiO2 buffer layer
- LithoLand modeler (based on differential method) used for all thick mask simulations. EMFLEX used also for validation.





Thin vs. Thick Mask



- Thin Mask make use of constant scattering approximation:

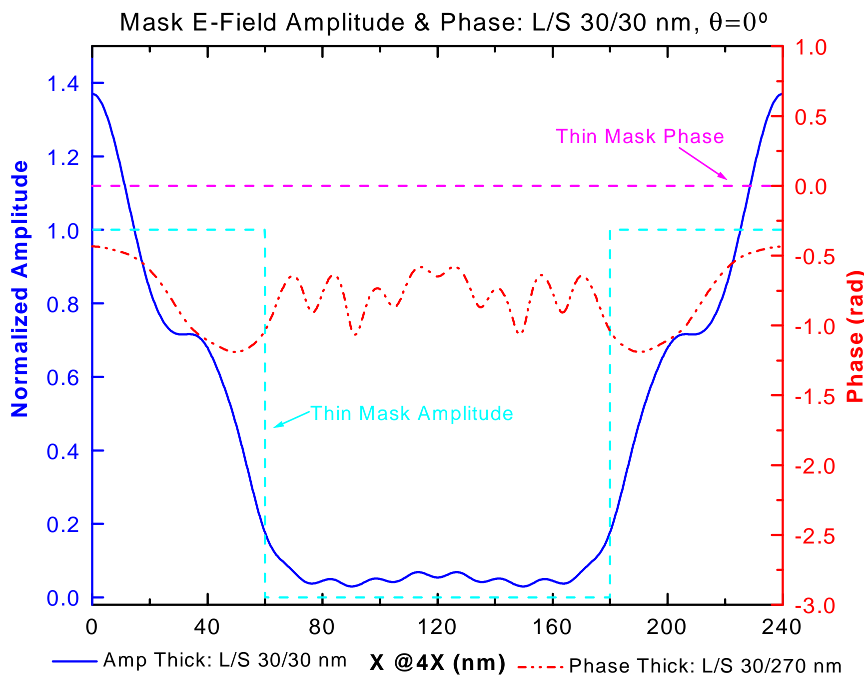
$S_0(\theta) = S_0\,(\theta=0)$; $S_{+1}(\theta) = S_{+1}\,(\theta=0)$; $S_{-1}(\theta) = S_{-1}\,(\theta=0)$; etc.

- Thick Mask require re-computation of the scattered field for each incidence mask angle.

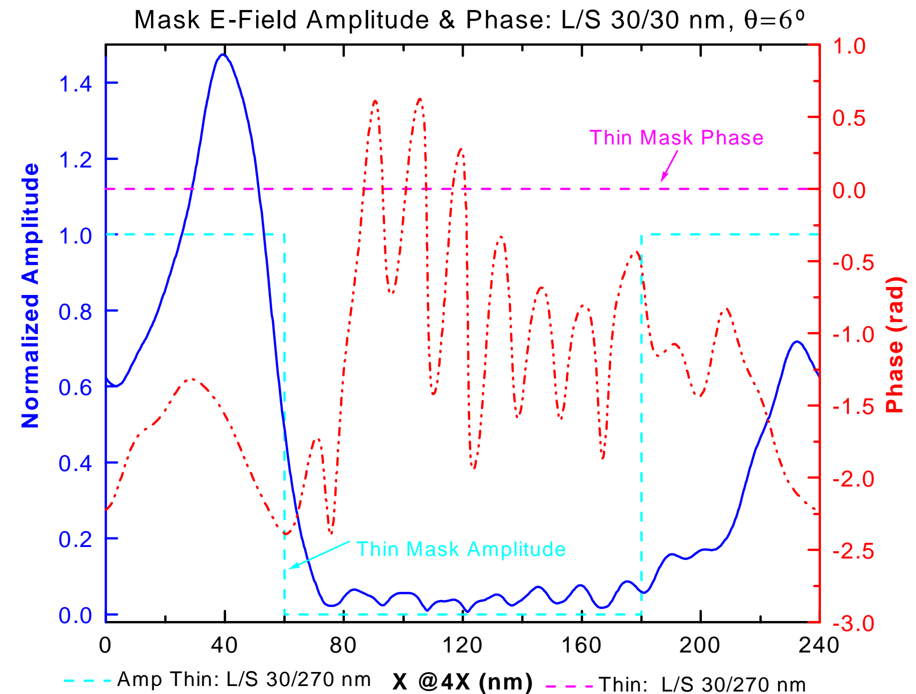
Amplitude and Phase for thick vs. thin mask

30 nm nested lines

at θ=0°



at θ=6°

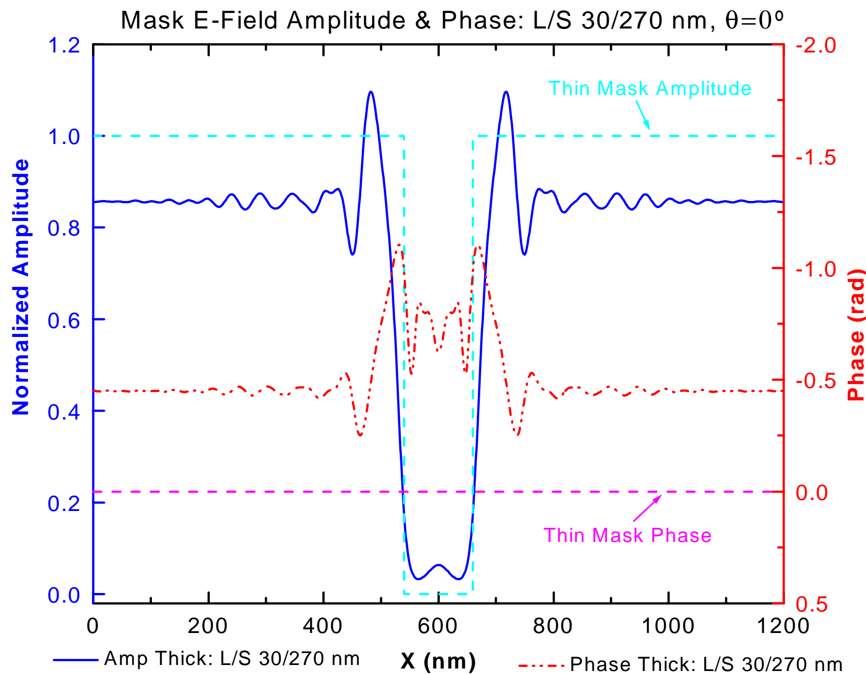


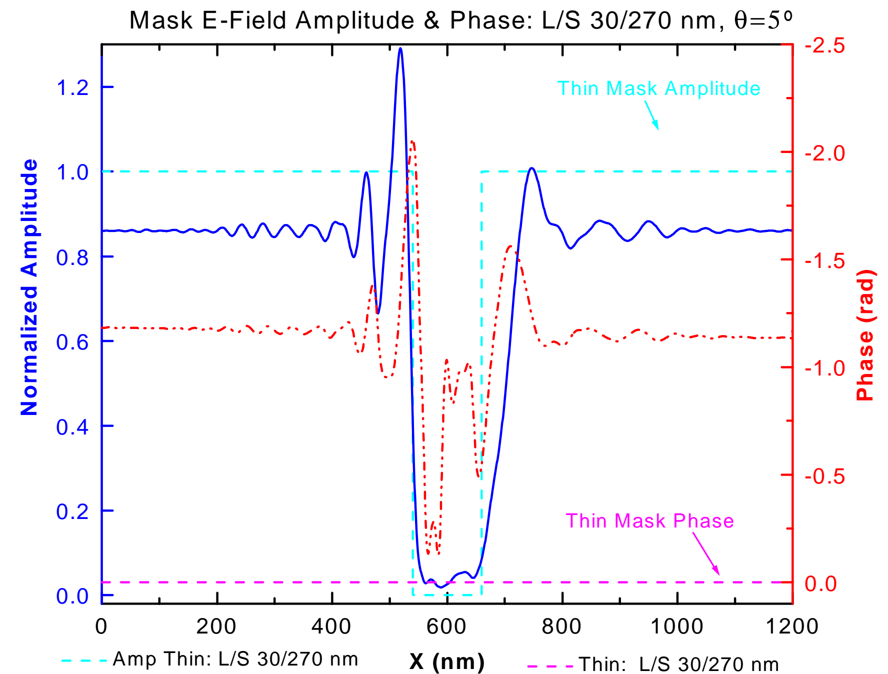
Amplitude and Phase for thick vs. thin mask

30 nm isolated line

at θ=0°

at θ=5°



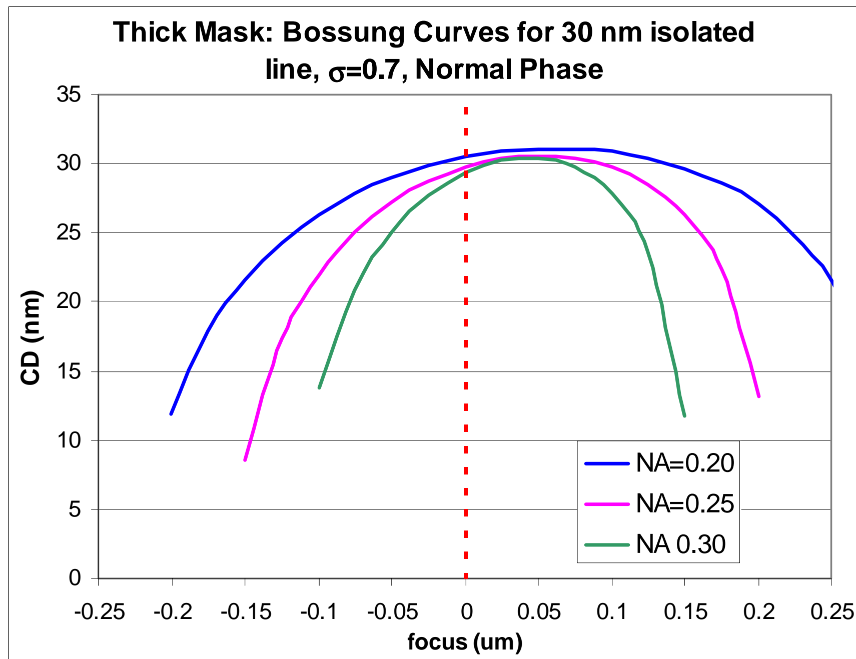


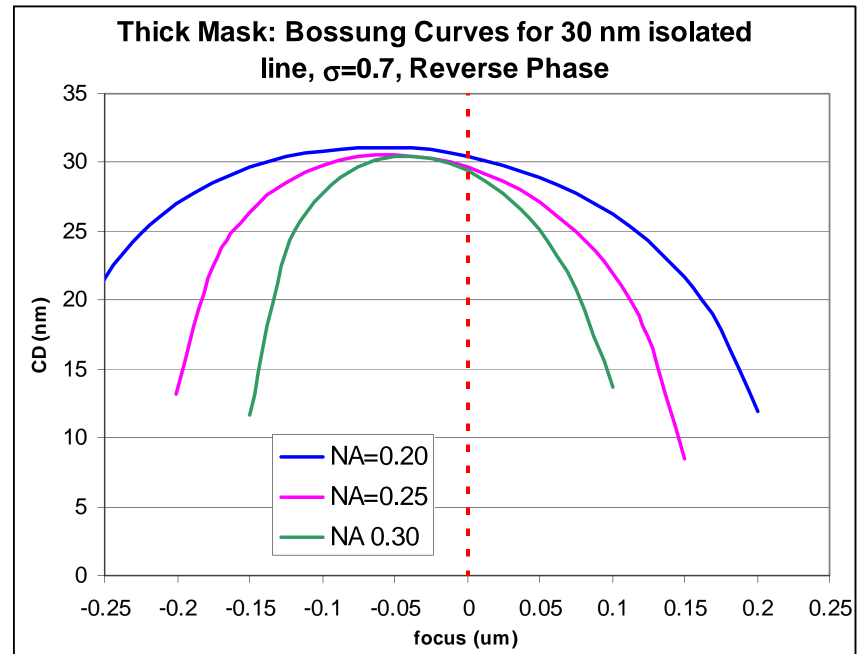
Asymmetry is caused by Thick Mask Phase

30 nm isolated line at $\theta = 0°$ for NA=0.2, 0.25, 0.3

Thick Mask with Normal Phase

Thick Mask with Reversed Phase

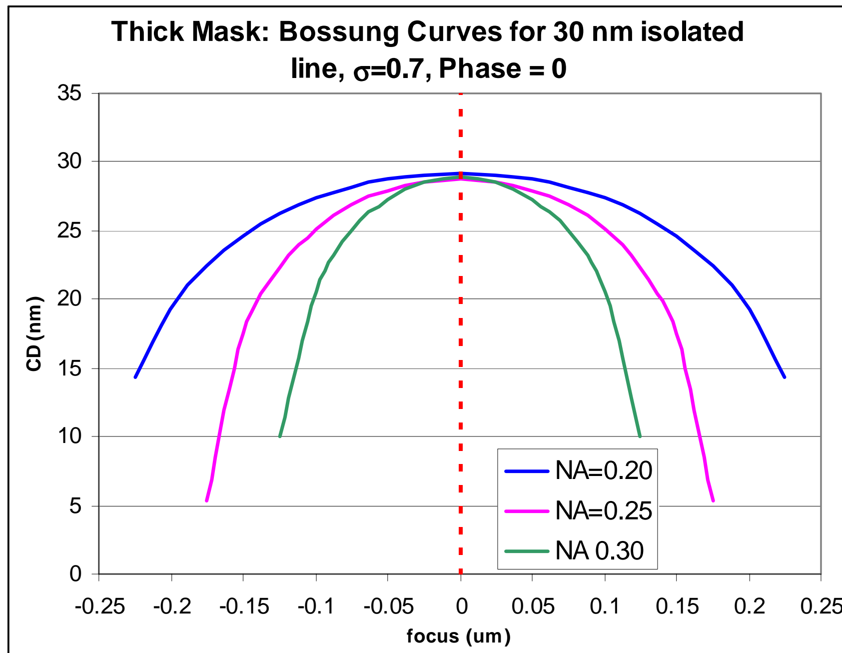


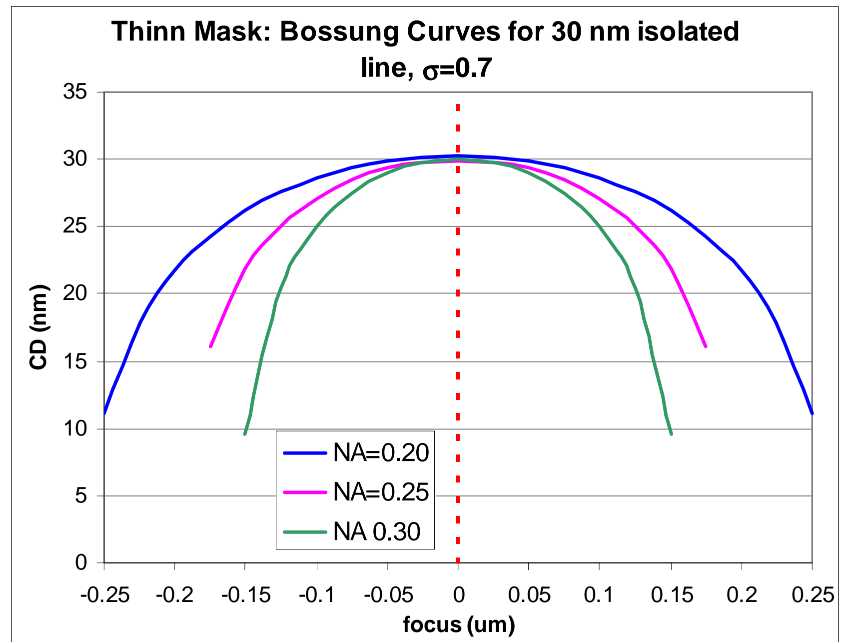


Bossung Asymmetry vanishes when the phase is arbitrarily set to zero, e.g. thin mask case

Thick Mask withPhase=0

Thin Mask Result

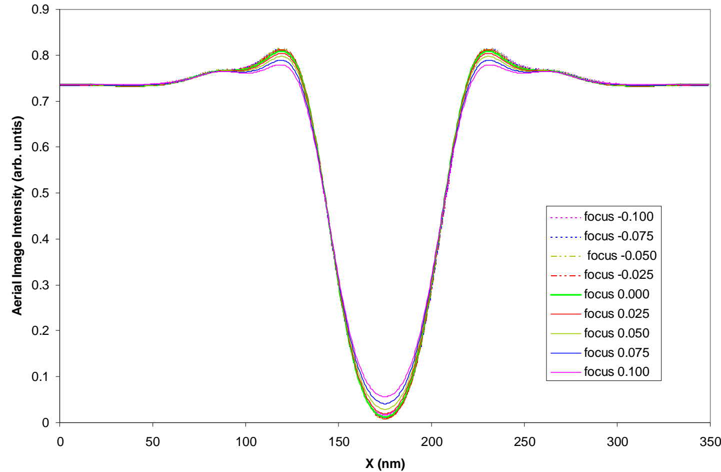


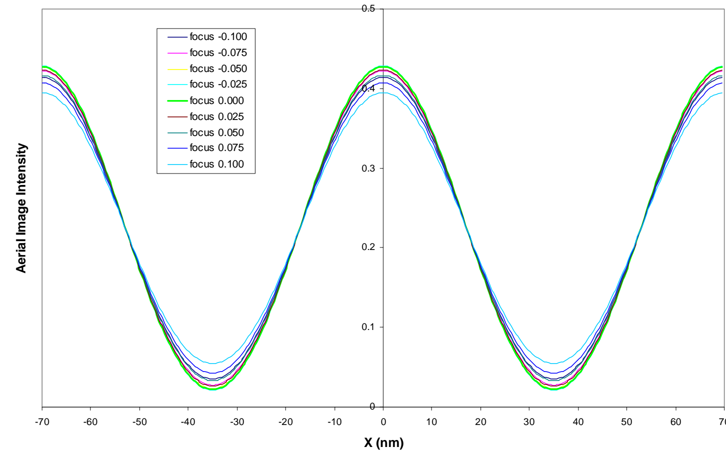


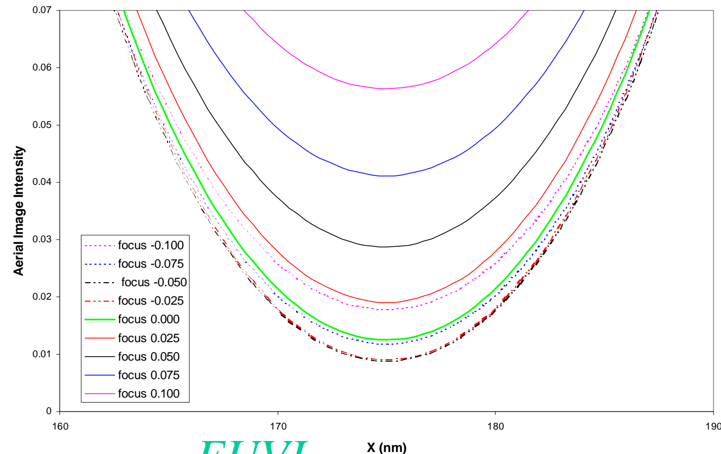
Thick Mask Comparison to EMFLEX also shows similar pattern dependent focus shift

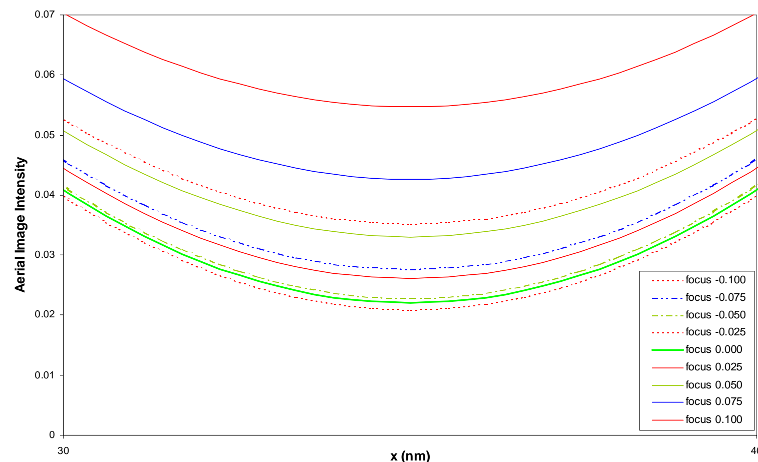
35 nm isolated line: ±0.1 um focus

35 nm nested line: ±0.1 um focus





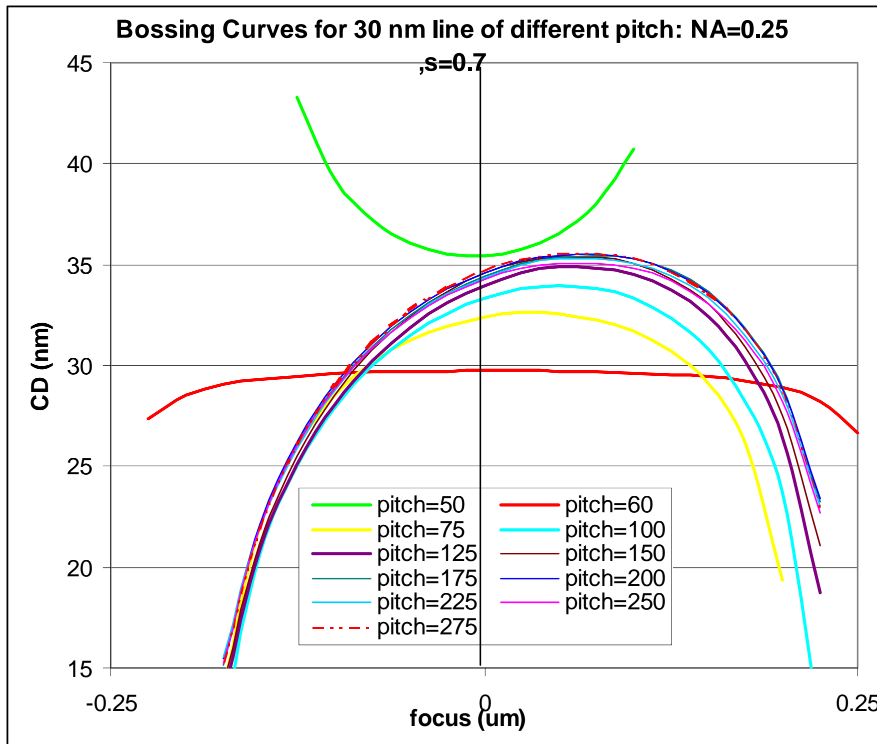


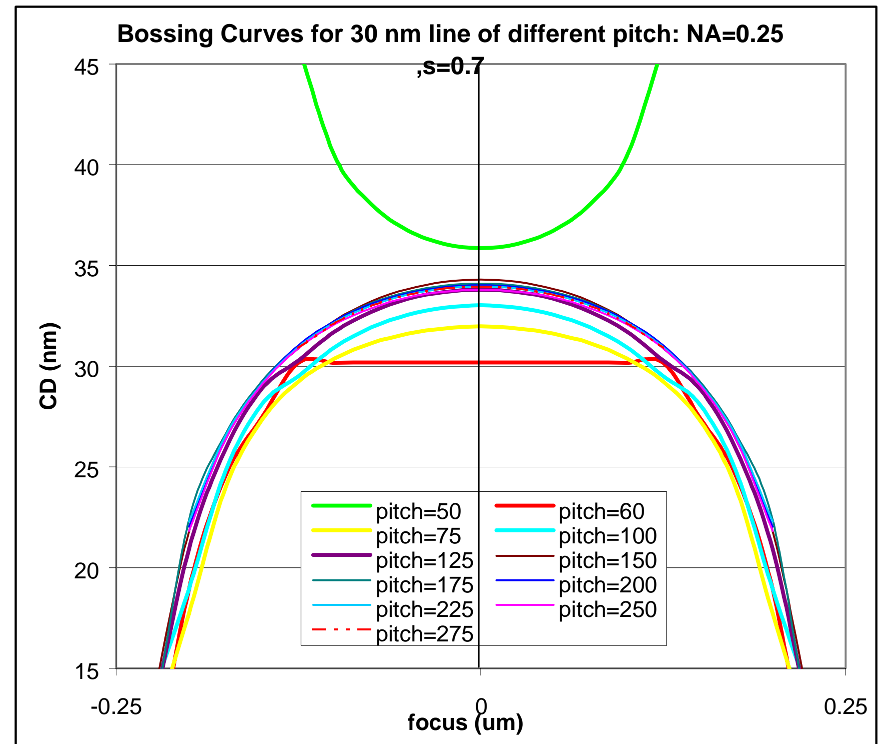


Bossung Shift/Asymmetry is pitch dependent for the thick mask case but independent of focus for the thin mask case

Thick Mask, $\theta=0^o$

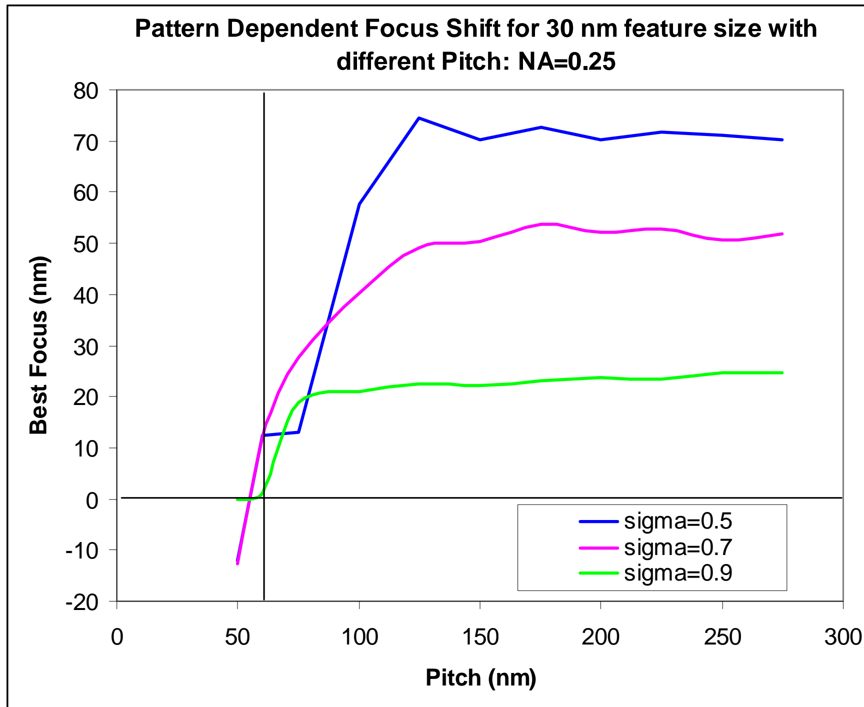
Thin Mask



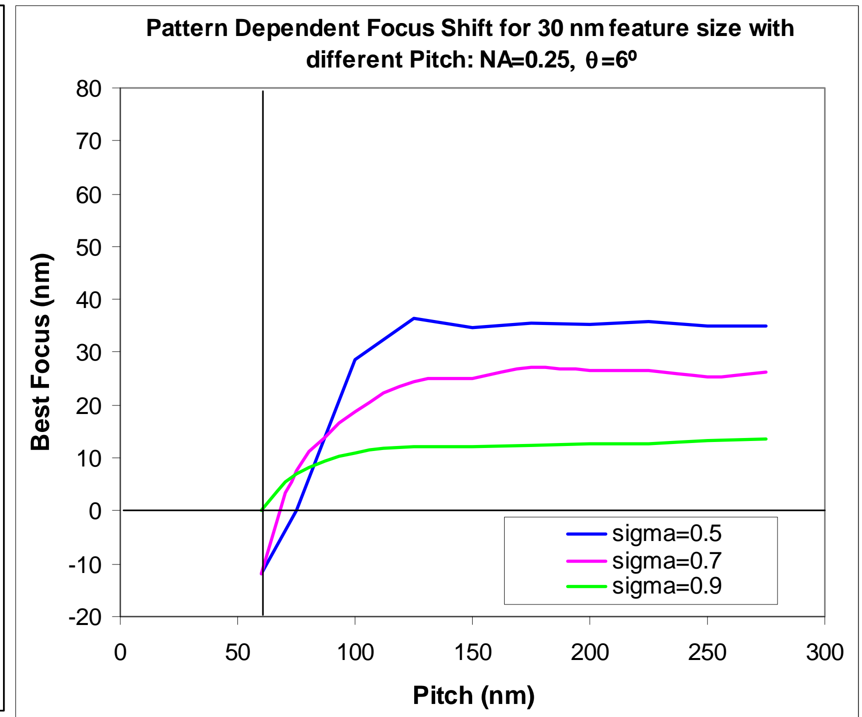


Focus Asymmetry is flattened through illuminator tilt

Thick Mask, $\theta=0^o$

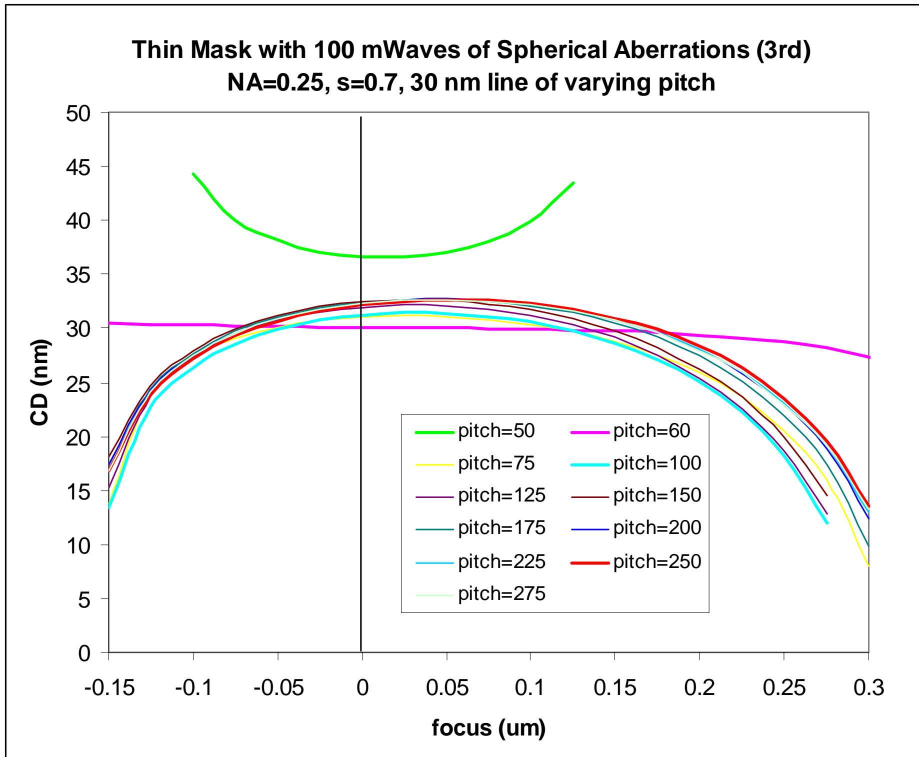


Thick Mask, $\theta=6^o$

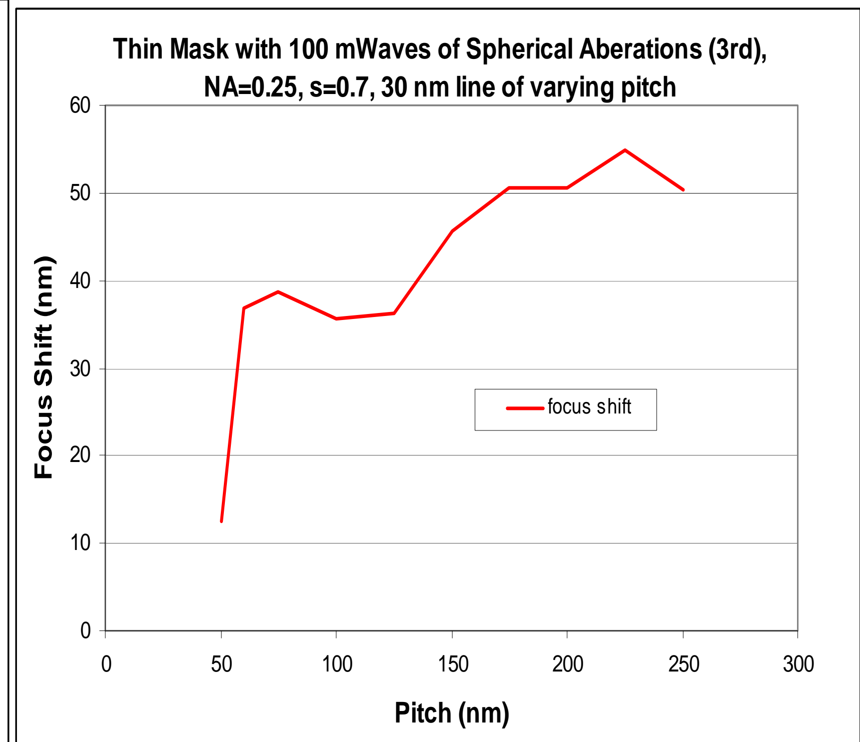


Thin Mask with Spherical Aberration also produces pattern dependent focus shift

Thick Mask with 100 mWaves Z9

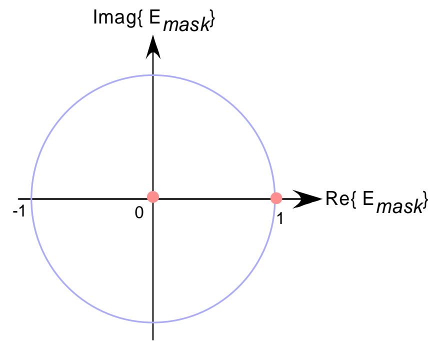


Corresponding Focus Shift with Pitch

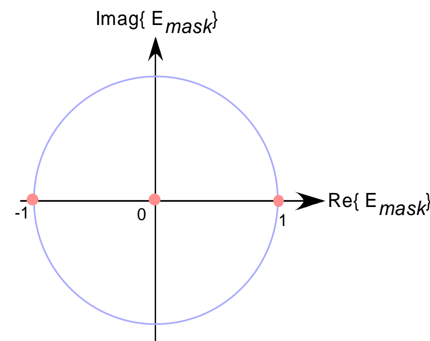


Comparison of Amplitude/Phase for standard thin & EUV mask

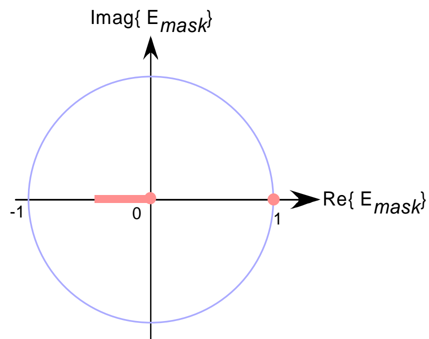
E-Field for Binary Mask (@ θ=0º)



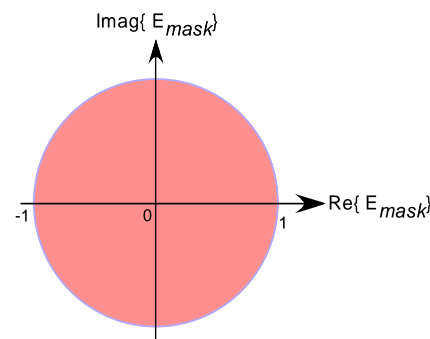
E-Field for aPSM Mask (@ θ=0º)



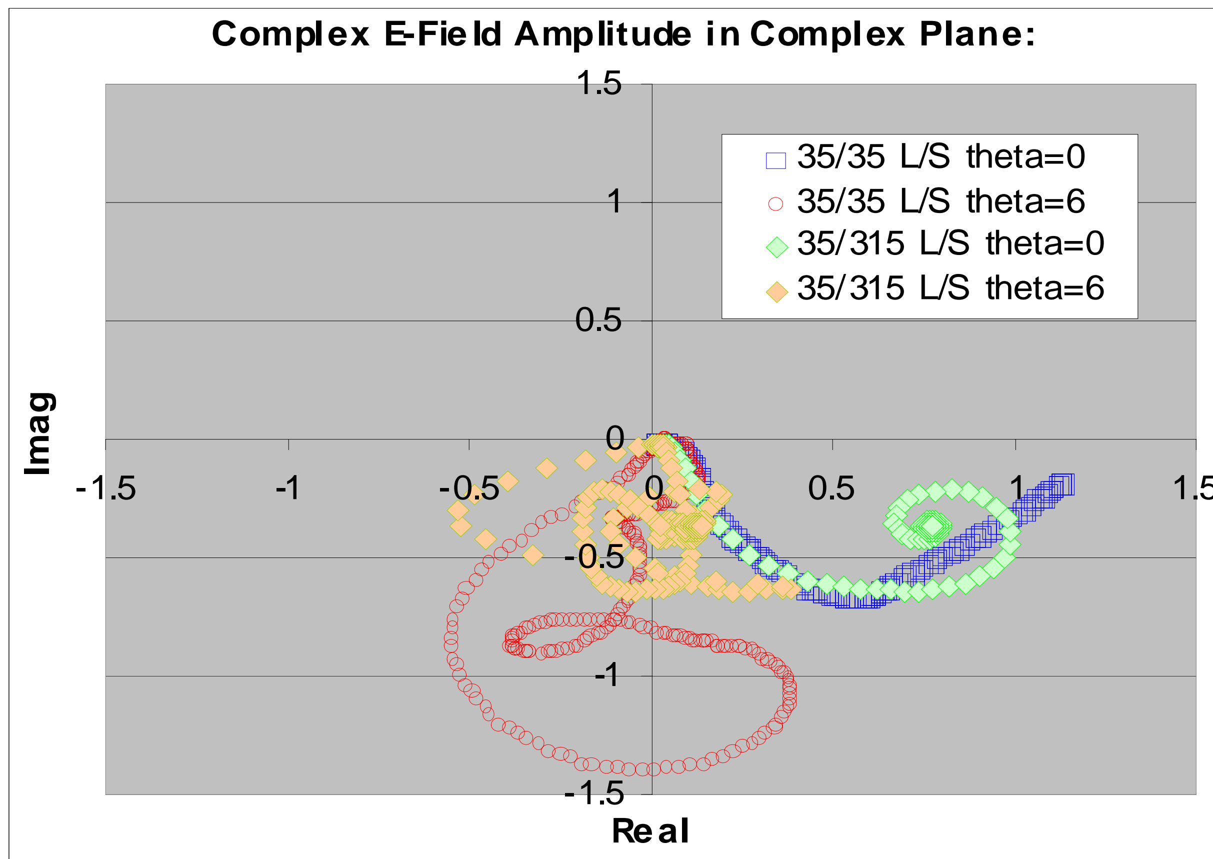
E-Field for attenuated PSM Mask (@ θ=0º)



E-Field for EUV Mask (@ θ=0º)



Complex Electric field Amplitude on top of mask wanders through complex plane



Focus shift appears to be independent of wavelength over the Si/Mo filter response

Si/Mo filter reflectivity Response

EUV Si/Mo Stack Spectral/Angular Reflectance

Effects of Wavelength on Aerial Image: q=6°, NA=0.25, s =0, 35 35 nmL S

iPHOTO->NA=0.25, s=0.7, l=13.4, L/S=35/315, slice=0.2

Conclusions

- Two different rigorous Mask simulators have shown independently pattern dependent focus shift and asymmetry in the Bossung curve for EUV Si/Mo masks.
  - LithoLand (based on differential method)
  - EMFLEX (based on time-domain Finite Element)
- Setting the phase of Complex Electric field arbitrarily to zero causes the shift to vanish.
  - The shift and asymmetry are hence attributed to the phase of the complex electric field that traces out a complex path over the clear and absorbing regions of the mask.
  - The focus shift is on the order of 50 nm between isolated and nested lines and not highly sensitive to the Numerical Aperture (NA). Higher σ reduces effect.
  - Wavelength averaging does not seem to significantly improve the focus shift.
  - System focus budget may be negatively impacted for high NA systems.
- The Asymmetry in the Bossung curve and the resultant pattern dependent focus shift is not observed for the thin mask case.
  - Thin mask with spherical aberrations seem to generate similar shifts as the EUV mask.

Acknowledgements

- This work was performed as an ASET project in the EUVL program and supported by NEDO.
- The authors acknowledge useful discussions and *LithoLand* support by Kenny Toh and Paul Davids of Intel (TCAD).